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Outdoor Exposure Results for Pretreated and Topcoated Aluminum Armor Alloys 2519, 5083, and 7039

by John V. Kelley and Brian E. Placzankis

ARL-TR-3283 **September 2004**

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Weapons and Materials Research Directorate, ARL

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14. Abstract

Over the last few decades, it has been determined that chemical treatments containing hexavalent chromium (Cr+6) are risks to both human health and the environment. One of the mainstays in corrosion prevention of aluminum alloys has been the use of chromate conversion coatings to promote adhesion and inhibit corrosion. Because of the push to reduce the use of Cr+6, many nonchromate treatments have been evaluated over the years. This report compares the relative performance of six nonchromate pretreatments with grit-blasted and chromated control samples in outdoor exposure at Cape Canaveral, FL. Recently obtained outdoor exposure data have been analyzed to determine the effectiveness of the pretreatments, indicating a different failure mode than typically seen in accelerated corrosion chambers. Corrosion attack at the edges is prevalent in outdoor exposure, while attack at scribe is uncommon. The substrate of most concern, aluminum 2519, seemed to be less of a factor than originally anticipated when no pretreatment was used. All samples have been monitored throughout the test using electrochemical impedance spectroscopy. Adhesion tests were performed upon completion of outdoor exposure. The data is compared with earlier accelerated corrosion data performed on matching samples.

15. SUBJECT TERMS

outdoor exposure, marine exposure, nonchromate, chromate, aluminum armor, impedance, salt fog, cyclic salt spray

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1. Introduction

The automotive and defense industry have been relying on accelerated corrosion data to determine relative corrosion performance of alloys and coating systems for decades. These methods are particularly valuable in determining the ability of coatings to protect steel from corrosion. However, the use of salt fog testing to determine the corrosion behavior of coated aluminum alloys is not as accurate (*1*). For this reason, outdoor exposure is a useful tool to validate accelerated corrosion data and is the most realistic method of evaluating corrosion performance.

The U.S. Army is continually seeking to lighten the force in an effort to increase its mobility and deployability. The use of aluminum armor alloys in the construction of armored vehicles is one of the most efficient ways to achieve this. However, aluminum armor can introduce new challenges in corrosion protection. For example, the mainstay in corrosion prevention of aluminum alloys, and the most effective to date, has been the use of chromate conversion coatings. Aluminum alloys are often pretreated with chromate conversion coatings to stabilize the native oxide on the surface of the metal to promote adhesion and inhibit corrosion. However, over the last few decades, it has been determined that chemical treatments containing hexavalent chromium (Cr+6) are risks to both human health and the environment. Therefore, the Army and private industry have been challenged with developing environmentally benign pretreatments for aluminum armor alloys.

Al 5083-H131 and 7039-T64 are used for the bulk of lightweight armor applications. Currently Al-Mg 5083 is the most widely used aluminum armor alloy because of its high ductility and resistance to stress corrosion cracking (SCC) (*2*). It has been used in armored systems such as the amphibious assault vehicle (AAV) and the Bradley fighting vehicle. Alloy 7039 has high strength and provides better ballistic protection but is more susceptible to stress corrosion cracking and less suitable for structural applications in marine/tropical environments. The continuous need to lighten the force while improving armor protection has led to the investigation of other aluminum alloys.

In recent years, Al 2519-T87 has been looked at as a possible replacement for 5083 in some applications. Its superior ballistic performance and high strength-to-weight ratio would help lighten the overall weight of the vehicle while providing better ballistic protection. Alloy 2519 was recently selected for the advanced amphibious assault vehicle (AAAV). The AAAV is one of the weapon systems presently under development by the Marine Corps to eventually replace the AAV. Alloy 2519 must be used with care in marine applications because of its susceptibility to pitting corrosion (*3*). Chemical agent resistant coating (CARC) coated 2519 samples have performed poorly in accelerated corrosion tests, regardless of the pretreatments used.

Avoiding corrosion of the metallic components in armored vehicles has always been a challenge. Since the Environmental Protection Agency has targeted hexavalent chrome for elimination and 2519 is becoming more common in armored systems, the task has become even more difficult. There are many nonchromate alternatives on the market today but, as yet, none have proven to be as effective as chromate in various accelerated corrosion tests.

The Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL) developed and executed a research program under the auspices of the Department of Defense Strategic Environmental Research and Development Program (SERDP) to examine commercially available nonchromate alternatives for the protection of aluminum alloys.

The goal of this effort was to assess the effectiveness of several nonchromate alternatives on coated test panels of three aluminum armor alloys. Included in the program were samples that were subjected to outdoor marine exposure. A study conducted by Dante et al. (*1*) suggests that to get meaningful results from outdoor exposure tests, more than 2 years are needed. The results in this report are of samples that completed 4 years of outdoor exposure and will be used to attempt to validate the earlier accelerated corrosion data and gage the relative corrosion performance of three aluminum alloys. Electrochemical impedance spectroscopy (EIS) and adhesion tests were also used to evaluate the condition of the topcoats.

2. Experimental Procedure

The selection of nonchromate conversion coatings to be tested was done in conjunction with study partners from the National Center for Manufacturing Sciences (NCMS), University of Michigan (*4*). Thirteen vendors of nonchromate coatings were asked to coat test panels. Of these, four vendors (for a total of six nonchromate coatings) agreed to have their coatings evaluated. For control purposes, a chromate conversion coating and a grit-blasted condition were also included (*5*). The notations used to identify all of the pretreatments and coatings in this study are listed in table 1.

Table 1. Description for notations used for coatings and pretreatments.

Notation	Coatings/Pretreatment
Grit blasted	Grit-blasted panel with no conversion coating
Chromate	Alodine 1200
Chemcote	Brent Chemcoat L497260A
Turcoat	Turco Alcoat 6787
Patclin 1	Patclin 1910A
Patclin 2	Patclin 1910B
Patclin 3	Patclin 1910C
Bulk Chemical	Bulk Chemical E-CLPS 923
CARC/topcoat	CARC (*6*)
Primer	Epoxy primer (*7*)

At the beginning of the program, ~300 aluminum panels nominally 4 × 6 × 0.375 in, (10 × 15 × 1 cm) of alloys 2519-T87, 7039-T64, and 5083-H131 were machined from rolled armor plate stock and sent to vendors and Army depots for coating application. Twelve panels for each conversion coating/alloy combination were prepared. From each set of 12 panels, 5 were painted with an epoxy primer (*7*) and CARC (*6*) topcoat, 3 panels were coated with the epoxy primer only, and 4 panels were left in the conversion coated state.

From the five sets painted with the CARC system, two sets (a total of 48 panels) were selected for outdoor exposure and are the topic of this study. All specimens and their designations are tabulated in Appendix A. Each of these panels was "X" scored using a hardened steel scribe with a static load of 5 kg and placed on a rack on the beach at Cape Canaveral Air Force Base, FL (figure 1). A hole was drilled in each panel near the edge and was used to attach the "working electrode" lead with a screw for impedance measurements. The panels were propped up at about 30° horizontally, with screw holes on top so water would drain away from hole. The racks were positioned approximately 100 yards away from and facing the ocean. Each panel was held in place 1.25 in above the surface of the rack using Teflon* brackets. Teflon was used because of its inert qualities, durability, and electrical insulating properties (figure 2). The other seven sets of panels were tested in an earlier study using accelerated test methods and EIS (*5*).

Figure 1. Exposure racks at Cape Canaveral.

* Teflon is a registered trademark of DuPont.

Figure 2. Teflon hold-down brackets.

Periodic visual inspections were performed at 6, 9, 19, and 48 months outdoor exposure, and the condition of the surface of the panel was estimated and recorded in terms of percent area failed. At the end of the 48-month exposure, the surface of the panel was evaluated according to ASTM D 1654-79A (*8*). Procedure B was used to rank the areas away from the scribe, and procedure A was used to obtain ratings for creepage outward from the scribe. The rating criteria for ASTM D 1654-79A are outlined in tables 2 and 3.

Table 2. Rating criteria of procedure A for evaluating creepage from scribe of painted panels subjected to corrosive environments (*8*).

Millimeters	**Inches (Approximate)**	**Rating No.**
Over 0	0	10
Over 0 to 0.5	0 to 1/64	9
Over 0.5 to 1.0	1/64 to 1/32	8
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4
Over 7.0 to 10.0	1/4 to 3/8	3
Over 10.0 to 13.0	3/8 to 1/2	2
Over 13.0 to 16.0	1/2 to 5/8	1
Over 16.0 to more	5/8 to more	0

Table 3. Rating criteria of procedure ASTM 1654-79A procedure B for evaluating unscribed areas of painted panels subjected to corrosive environments (*8*).

Area Failed (%)	Rating No.
No failure	10
0 to 1	9
2 to 3	8
4 to 6	7
7 to 10	6
11 to 20	5
21 to 30	4
31 to 40	3
41 to 55	2
56 to 75	1
Over 75	0

EIS was employed to monitor coating condition over time. A portable EIS apparatus was designed to allow measurements to be taken at remote sites in the field (figure 3). It consisted of a Schlumberger 1280 combination frequency response analyzer (FRA)/potentiostat, a 12-V DC to 120-V AC power inverter with 12-V battery, and a Toshiba laptop computer. Periodic measurements were taken at 6, 9, 19, and 48 months of exposure using the cell configuration illustrated in figure 4. The cell was filled with 25 mL of 0.5 N NaCl solution and allowed to equilibrate for at least 2 hr prior to taking measurements. The software package Zplot was used for data acquisition and Z view for data analysis. Measurements were taken at the corrosion potential of the sample over the frequency range of 100 kHz–0.01 Hz. The single sine technique was utilized, with a sinusoidal potential impressed upon the open circuit corrosion potential of the substrate (–0.930 V vs. saturated calomel electrode [SCE]) and an applied 80-mV amplitude. An attempt was made to attach the cell and take measurements on a different spot on the panel for each inspection period. That wasn't always possible because, as the samples degraded over time, the amount of defect-free area to perform EIS became limited on some samples.

The EIS data was plotted and evaluated in Bode and Nyquist formats. The Bode formats displayed the magnitude (log | Z |) and phase angle (θ) of the impedance as a function of applied frequency (log f). The total impedance of the specimen, defined as the log | Z | value at 10 mHz in the Bode magnitude plot, was also plotted as a function of exposure time for comparison of the effectiveness of each coating system.

Postexposure paint adhesion tests were performed using a HATE Mark VII coating adhesion tester (figure 5) in accordance with ASTM D 4541 (*9*). A loading fixture commonly referred to as a "dolly" was secured normal to the coating surface using a cyanoacrylate adhesive. After allowing the adhesive to cure for 24 hr in laboratory conditions (table 4), the attached dolly was

Figure 3. Schematic of EIS cell used for field measurements.

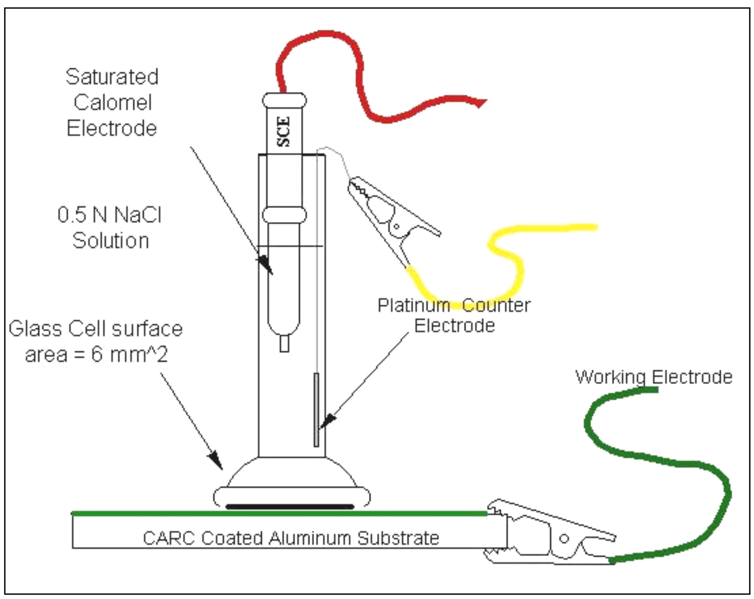


Figure 4. Portable EIS setup at outdoor exposure test site at Cape Canaveral.

inserted into the test apparatus. The load applied by the apparatus was gradually increased and monitored on the gauge until a plug of coating was detached. The failure value in lb/in^2 (psi) was recorded and the failure mode characterized. For this test to be accurate, the panels must be sufficiently thick to ensure that the coaxial load applied during the removal stage does not distort the substrate material and cause a bulging or a "trampolining effect." On a thin specimen, the resultant bulge caused the coating to radially peel away outwards from the center instead of uniformly pulling away in pure tension, thus resulting in significantly lower readings. All of the panels used in this study were made from 0.375-in-thick aluminum armor and were of adequate thickness for the pull-off test procedure.

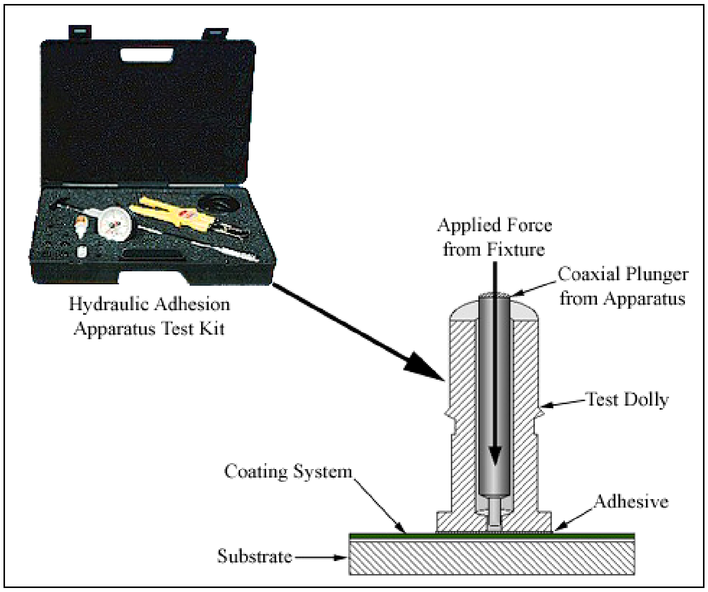


Figure 5. Schematic of the pull-off adhesion test performed on all exposed samples.

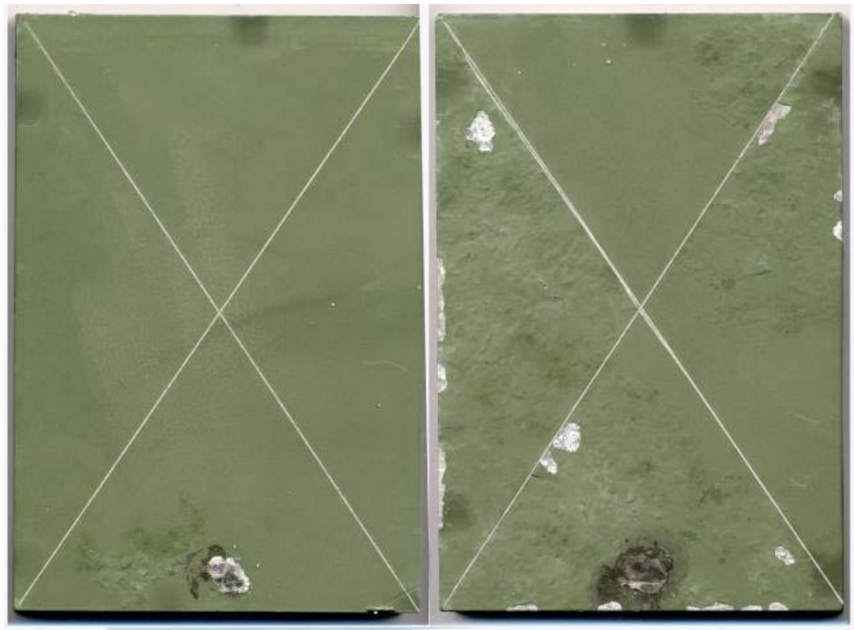
Table 4. Laboratory conditions for pull-off adhesion (*9*).

Adhesive type	Cyanoacrylate
Cure time (hr)	24
Temperature (°C)	25
Relative humidity (%)	31
Substrate materials	Al 2519/5083/7039
Coating type	CARC 53022/53039A
Coating thickness (mil)	~4.0

3. Results

3.1 Visual Inspection

At each of the inspection intervals, every panel was visually examined, and any defects were noted. Some key photos are presented in figures 6–9. Note: regardless of the orientation of the photos, the bottom edge of the panel refers to the edge opposite the screw hole. One of the first observations made of all panels was of the noticeable fading of the paint at the 9-month inspection. At that time, it was also apparent that corrosion had begun on the edges of panels B, J, O, and P in set A, and panels A, I, L, O, Q, and R in set B (see appendix A). At 37 months, two of the sample sets were removed from the test because of excessive corrosion damage. They were P (7039/Patclin 2) and L (2519/Turcoat). All other samples completed the 48 months of exposure. When the test was terminated after 48 months, all samples were given a final thorough visual inspection. First, a general overall condition of the panels was estimated, and the average of each alloy-pretreatment combination was taken. These results are illustrated in figure 10.



(a) (b)

Figure 6. Alloy 2519 pretreated with Turcoat.

(a) (b)

Figure 7. Alloy 7039 pretreated with Patclin 2.

(a) (b)

Figure 8. Grit-blasted 2519 after 48 months of exposure.

(a) (b)

Figure 9. Grit-blasted 7039 after 48 months of exposure.

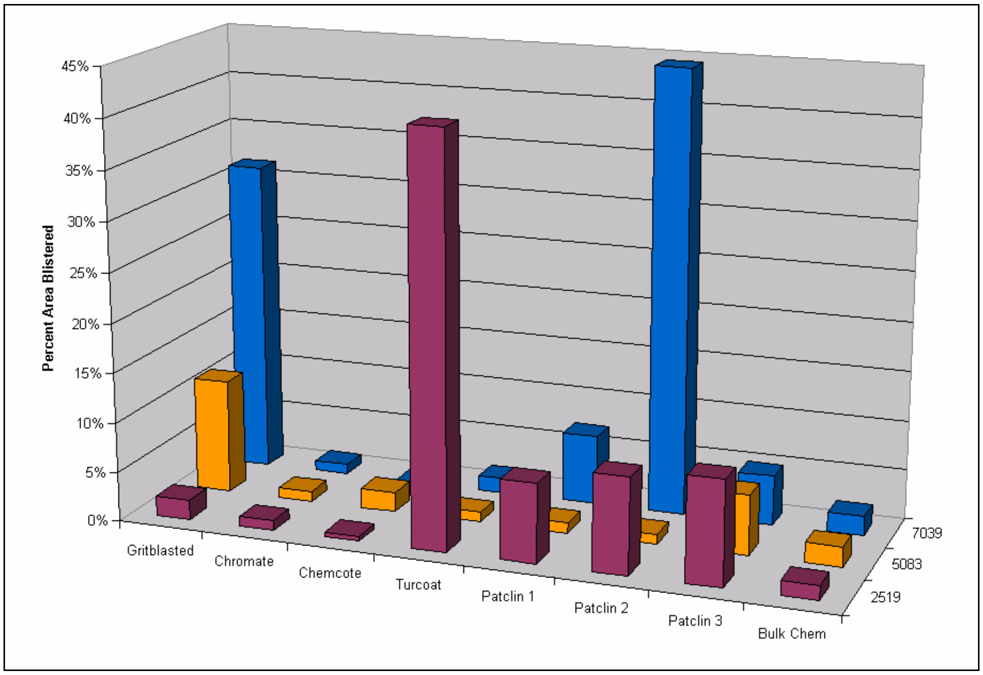


Figure 10. Average area failed of both sets of panels after 48 months (208 weeks) of outdoor exposure.

Unlike the subsequent evaluations done according to ASTM D 1654-79A, these data represented the overall condition of the top surface of the panel and took into account the corrosion near the edges and along the scribes.

Measurements of corrosion creepage outward from the scribes and the condition of the unscribed areas of the panels were done according to ASTM D 1654-79A procedures A and B, respectively. These results are shown in figures 11 and 12. For the evaluations of areas away from the scribe, an effort was made to discount any corrosion within 0.5 in from the edges and any corrosion initiating from the scribes. Despite these efforts, in several cases, the corrosion undercutting from the edges went beyond the 0.5-in boundary and therefore was included.

3.2 Electrochemical Impedance Spectroscopy (EIS)

EIS was used to measure the dielectric response of the coating as it degraded over the 48 months of outdoor exposure and compared with previously recorded laboratory measurements. The procedure for the laboratory measurements taken on immersion samples is described elsewhere (*5*). For the outdoor experiment, four measurements were recorded for each sample over the 48 months. These results are given in figures 13–17. The initial measurement was made in the lab on a similarly prepared sample. Measurements made at 6, 9, and 19 months were made on site at Cape Canaveral Air Force Base. The final impedance measurement was taken at 48 months for all samples and was done in the laboratory when the exposure test was terminated.

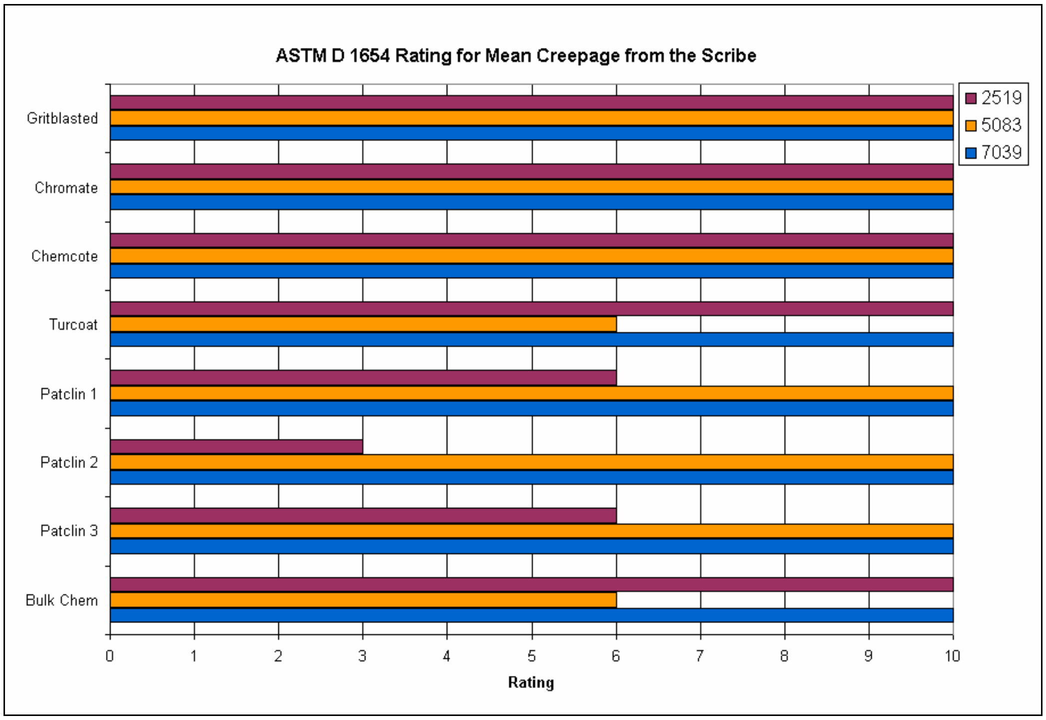


Figure 11. ASTM D 1654-79A procedure A ratings for panels in outdoor exposure.

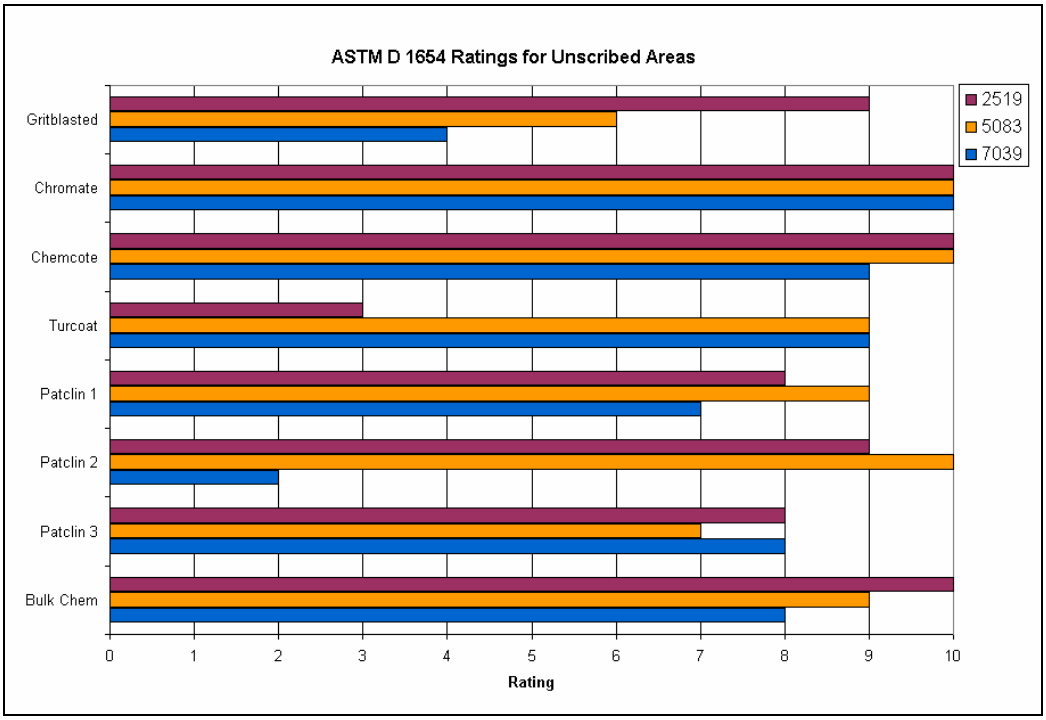


Figure 12. ASTM D 1654-79A procedure B ratings for panels in outdoor exposure.

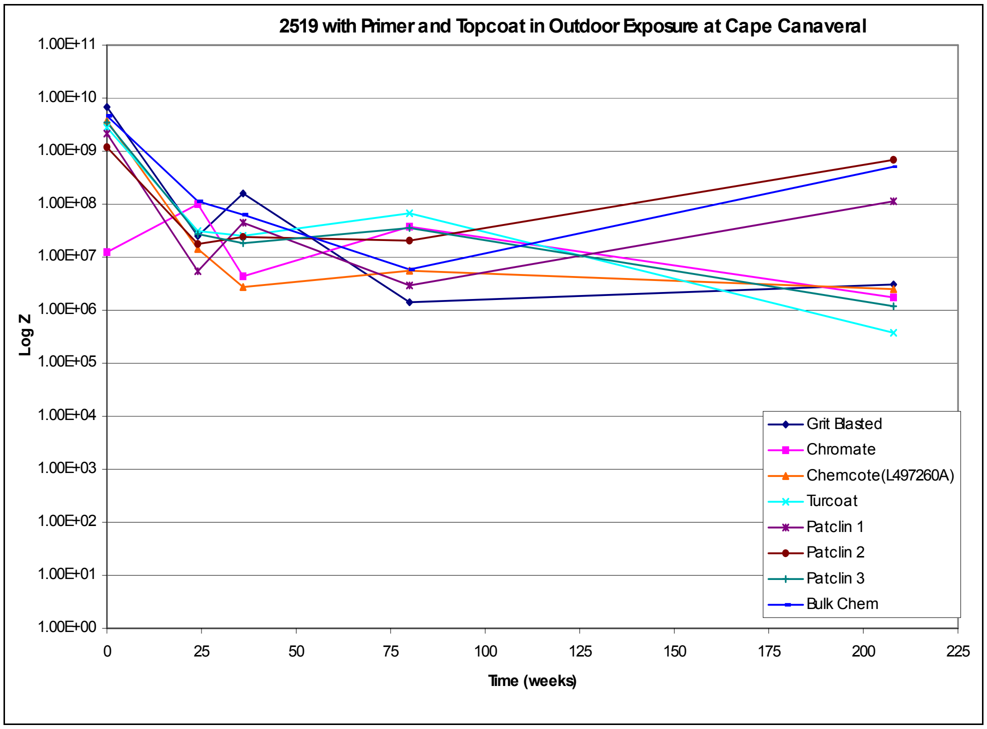


Figure 13. Al alloy 2519 in outdoor exposure.

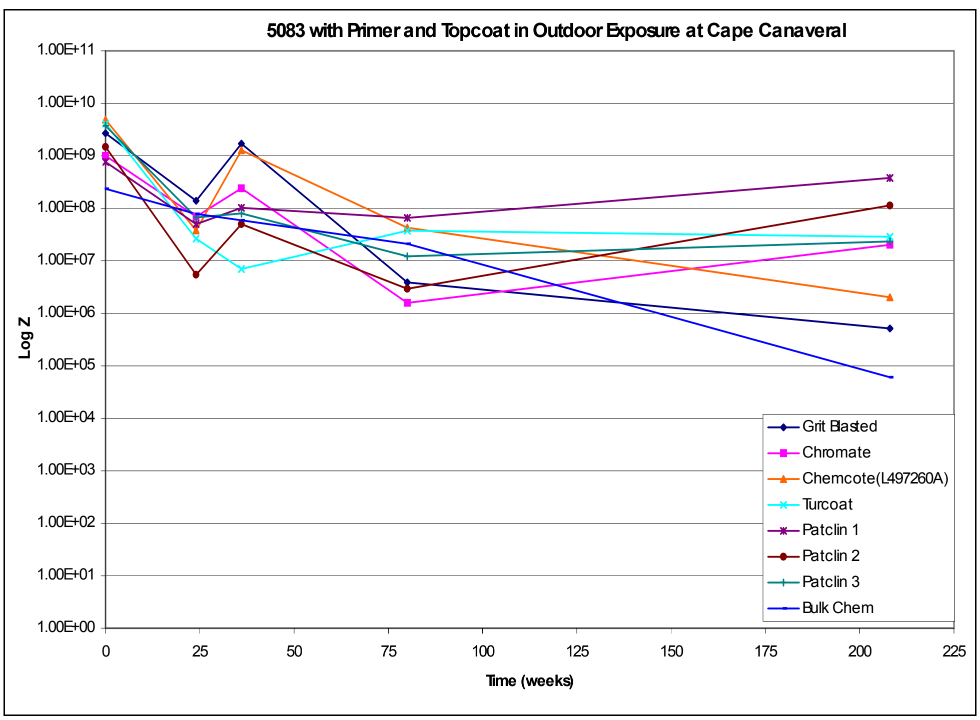


Figure 14. Al alloy 5083 in outdoor exposure.

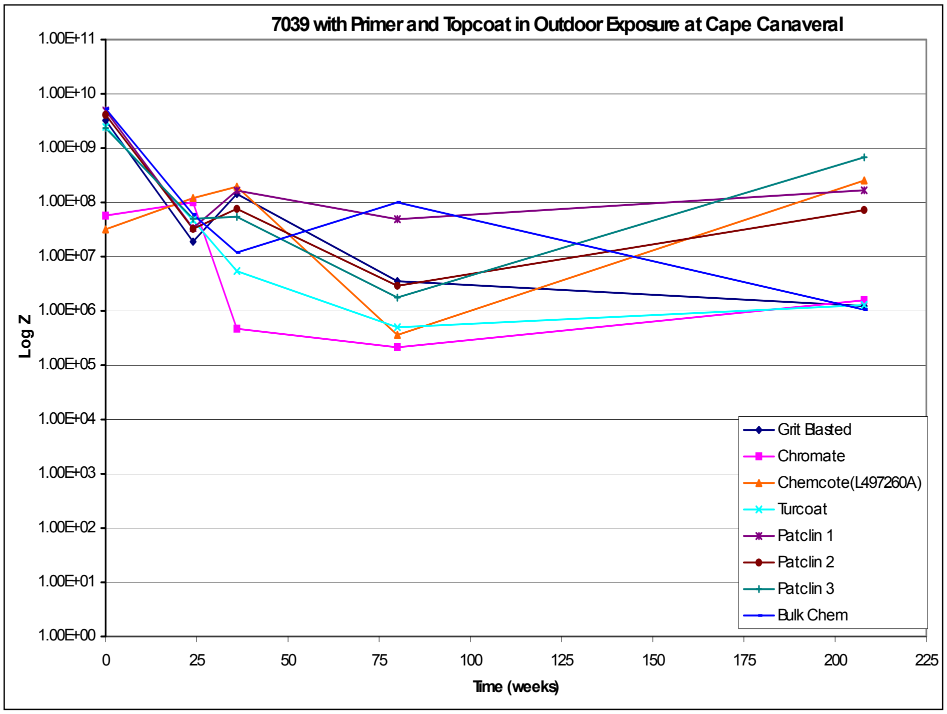


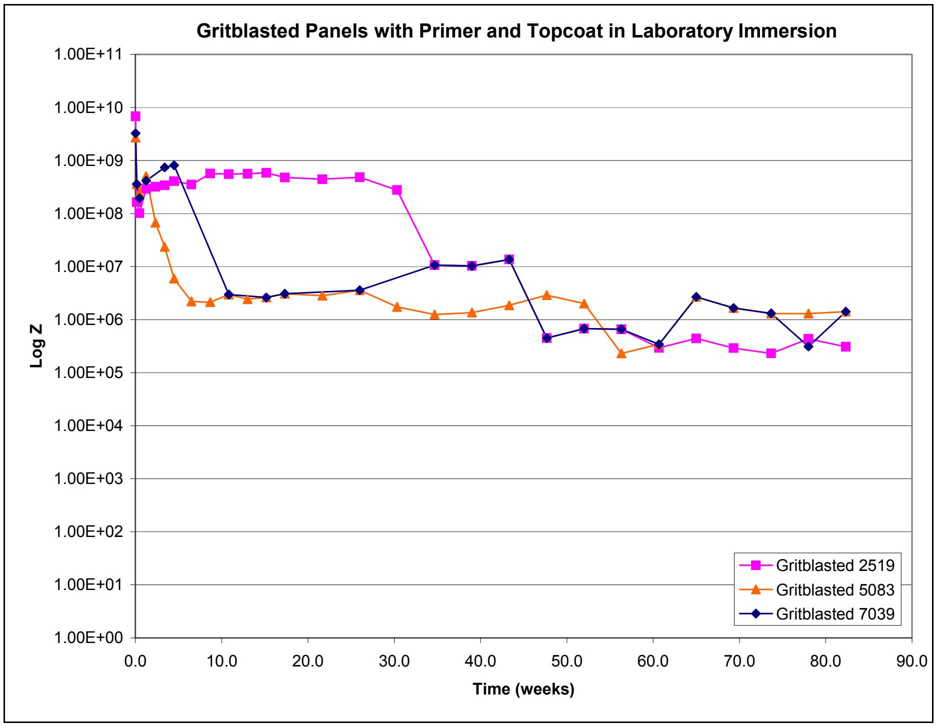
Figure 15. Al alloy 7039 in outdoor exposure.

3.3 Coating Adhesion

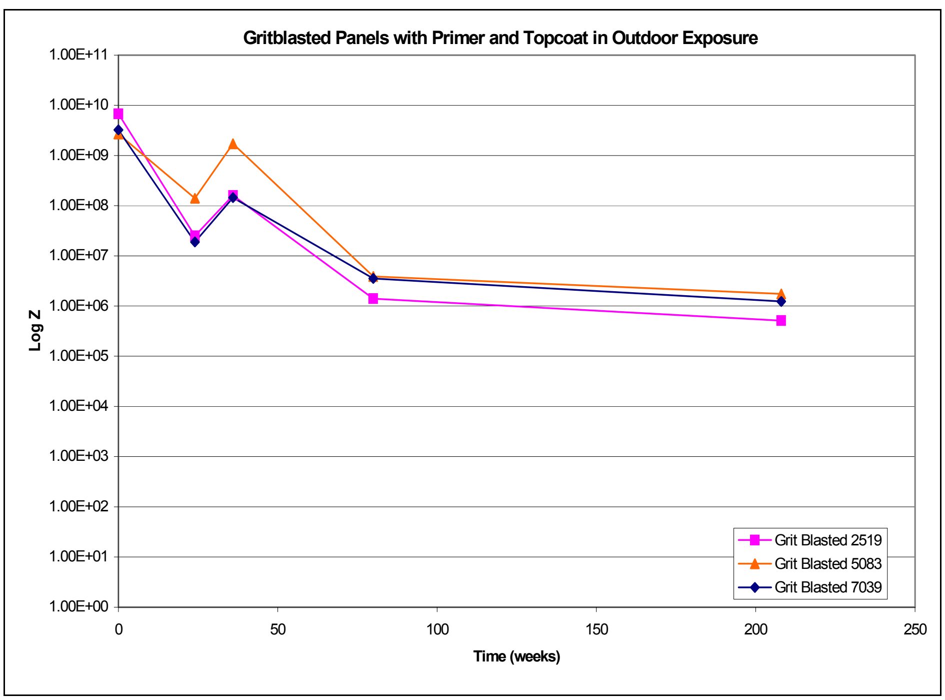
Postexposure coating adhesion tests were performed on all samples exposed. Two "pull-off" tests per panel were done, and the results for each alloy/pretreatment combination were averaged and illustrated in figure 18. All of the pull-off results, along with the statistics, are tabulated in appendix B. The mode of failure for each pulloff was noted and is given in appendix C.

4. Discussion

The objective of this effort was to evaluate commercially available nonchromate conversion coatings against a baseline of hexavalent chromate (Alodine 1200) and to characterize the corrosion mechanisms and adhesion performance of the coatings systems. This discussion will focus on the following two areas: (1) the performance of the pretreatments on each alloy in outdoor exposure and (2) a comparison of the corrosion observed and the relative performance of these coatings in outdoor exposure and accelerated corrosion tests.

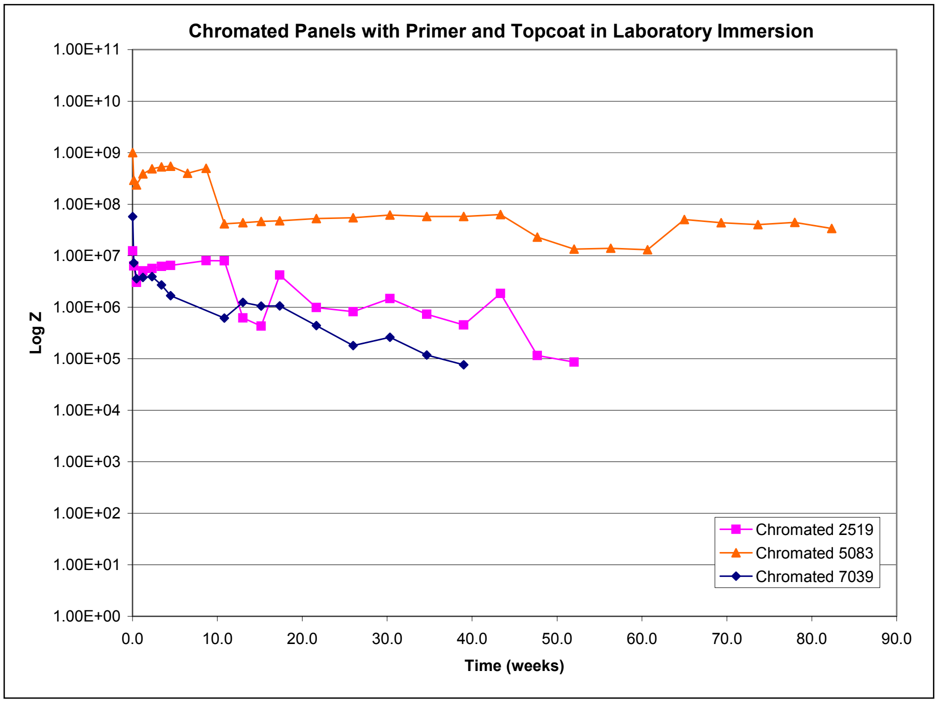


(a) In lab immersion

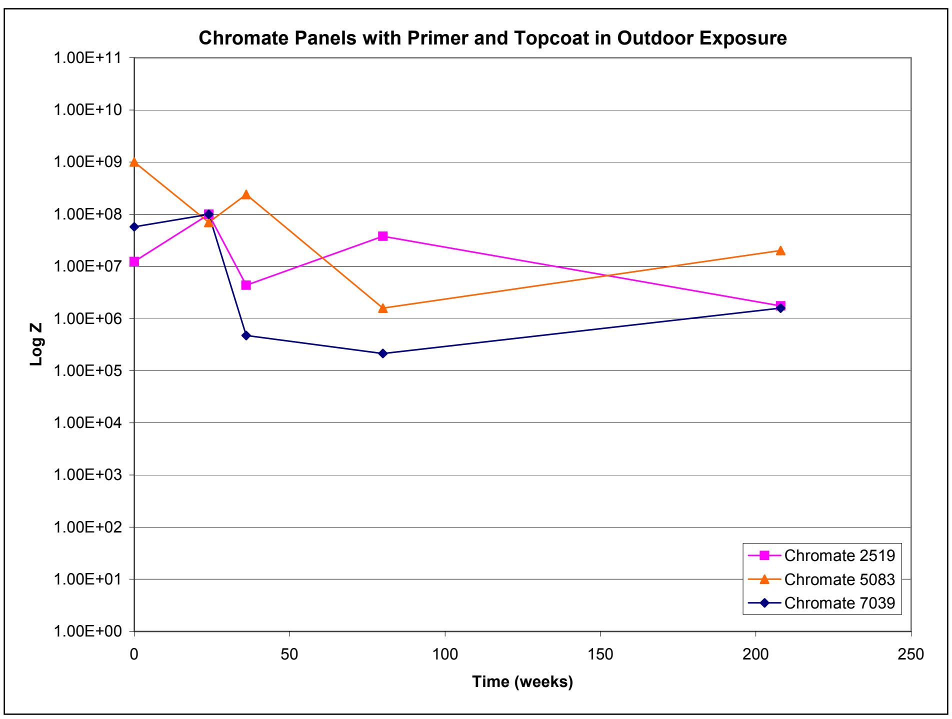


(b) In outdoor exposure

Figure 16. Grit-blasted panels in (a) lab immersion and (b) outdoor exposure.



(a) In lab immersion



(b) In outdoor exposure

Figure 17. Chromated panels in (a) lab immersion and (b) outdoor exposure.

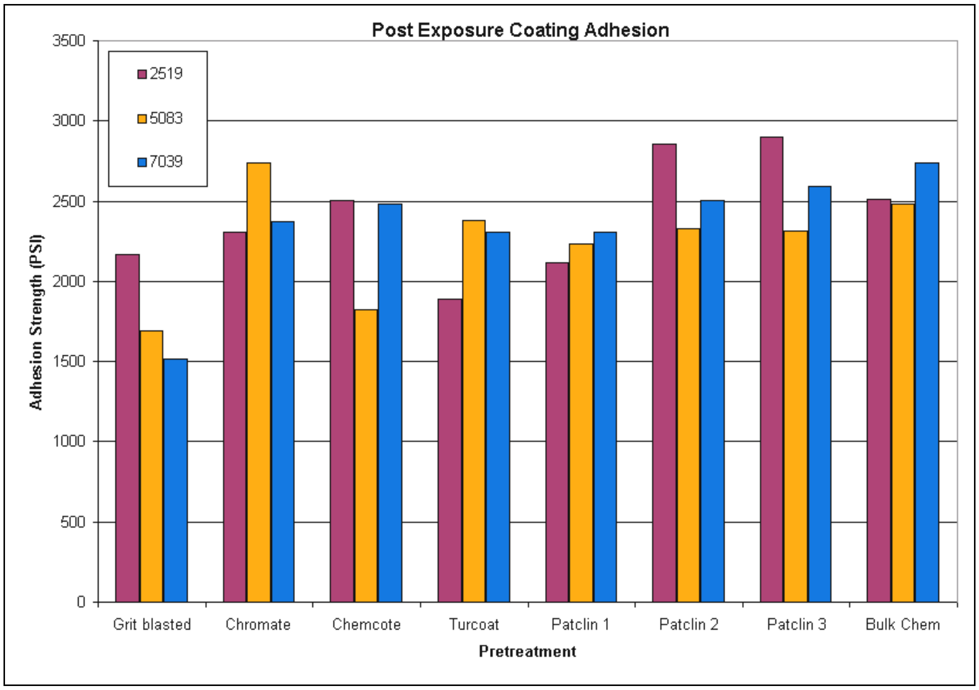


Figure 18. Averaged postexposure pull-off coating adhesion strength data.

The three alloys used in the study (Al alloys 2519, 7039, and 5083) have very different general corrosion characteristics. Alloy 2519 is generally very susceptible to pitting corrosion and considered difficult to pretreat due to the Cu containing precipitates and constituent particles found in the alloy microstructure. Alloy 5083, the most commonly used aluminum armor alloy, is very resistant to pitting corrosion, even if the alloy is tested "bare." Alloy 7039 is somewhat susceptible to pitting and can also suffer from stress corrosion cracking. Thus, it is anticipated that the conversion coating/organic coating systems will behave differently on each alloy.

Despite the general corrosion resistance of alloy 5083, some of the pretreatments performed poorly on this alloy. As shown in figure 11, most of the alloy/coating combinations showed no appreciable creepage from the scribes. However, creepback was observed for both the Turcoat and Bulk Chemical pretreatments on alloy 5083. ASTM ratings of the unscribed areas are given in figure 12, and, again, two pretreatments (Patclin 3 and grit blasting) showed significant performance drops on this alloy. The impedance plots for the coatings on 5083 are shown in figure 14, while the postexposure adhesion results are shown in figure 18. Neither the total impedance measurements nor the postexposure adhesion results provided a simple explanation for this behavior. Overall, several of the nonchromate conversion coatings performed well on this alloy, as did the Alodine 1200 control.

Alloy 7039 displayed the greatest resistance to creepage from the scribes but still had significant attack away from the scribe for some pretreatments (figures 11 and 12). The Patclin 2 and grit-blasted panels had ratings of 2 and 4, respectively, for unscribed regions. Again, results from

impedance as a function of exposure (figure 15) and postexposure adhesion (figure 18) did not provide much insight to this behavior. The impedance values of both these pretreatments were within the scatter band. The postexposure adhesion strength of the grit-blasted panels was somewhat lower (1515 psi) than the average value of 2367 psi attained by all the alloy 7039 specimens, but the Patclin 2 adhesion was 2505 psi, which was the third highest. Again, as with 5083, several of the nonchromate pretreatments performed well, as did the chromate control samples.

As previously mentioned, the high copper contents found in 2000 series aluminum alloys make them difficult to pretreat, and alloy 2519 is no exception. Despite this, several of the nonchromate pretreatments and the Alodine 1200 control performed quite well when tested in conjunction with the organic coating system in outdoor exposure. Five pretreatments showed no creepage from the scribe (figure 11), and five pretreatments had ASTM ratings of 9 or 10 for unscribed areas. Most surprising was the fact that the grit-blasted panels with no pretreatment fell into both these groups and compared extremely well with the chromate controls. Figure 8 shows scanned images of the grit-blasted 2519 panels after 48 months exposure, showing no creepback of the coating whatsoever. The only defect visible was a small blister beside the hole used to attach the working electrode contacts for impedance measurements, earning it a rating of 9. This result was so surprising that the alloy content of each 2519 panel was reverified via energy dispersive spectroscopy in a scanning electron microscope.

The second area of this discussion will compare the performance results of accelerated corrosion tests with the results of the same alloy pretreatment combinations in outdoor exposure. Observations of the predominant failure modes is also discussed. The initial evaluation of these nonchromate conversion coatings was based on ASTM B117 (*10*) salt fog and GM 9540P (*11*) data. The outdoor exposure results will attempt to validate the initial findings.

After 100 cycles of GM 9540P, 7039 had only two cases of blistering near the scribe, fewest of the three alloys. Because all of the pretreatments on 7039 performed relatively well compared to chromate, no nonchromate conversion coatings emerged as the best for 7039. In outdoor exposure, 7039 samples had no measurable corrosion attack initiating at the scribes—again, the fewest cases of all three alloys. Corrosion initiating at the edges of samples caused the majority of the damage on this alloy in outdoor exposure. Chemcote was marginally better at resisting corrosion at the edges than the other nonchromate pretreatments for 7039 in outdoor exposure, but none were as good as chromate at resisting undercutting at the edges.

Accelerated corrosion testing proved to be disastrous for nonchromate conversion coatings on 2519. Total failure was seen on 2519 with all but three surface treatments—grit blasted, chromate, and Chemcote, with chromate performing best. However, as mentioned earlier, the 2519 samples performed much more admirably in outdoor exposure, with the biggest apparent surprise being the grit-blasted 2519 samples with no pretreatment. Although unexpected, the impressive performance of the grit-blasted 2519 panels was not in conflict with the accelerated

corrosion results. In the earlier work, the grit-blasted 2519 was one of three that did not experience “total failure” after 100 cycles of GM 9540P. Also in agreement was the good corrosion performance of the Chemcote on 2519. Turcoat (figure 6) and all the Patclin treatments on 2519 did not fair as well, which is also consistent with the previous work.

The exceptional resistance to general corrosion of 5083 was evident in the results of the accelerated testing data. In general, 5083 was clearly the best performer of all three alloys as long as it was pretreated. However, when 5083 was grit blasted and without a pretreatment, significant blistering occurred. This correlated well with the outdoor exposure data where six out of the seven pretreatments on 5083 rated a 9 or above (figure 12) and grit blasted only scored a 6 rating. Alodine 1200 performed best in both accelerated corrosion and outdoor exposure tests on 5083. However, if not for the corrosion along the edges of the panel, an argument could be made for Chemcote and Patclin 2 as the best in outdoor exposure.

In outdoor exposure, corrosion attack at the scribe was relatively uncommon, contrasting what is typically seen in accelerated corrosion tests. Only 5 out of the 24 pretreatment/alloy combinations (about 21%) experienced any measurable creepage from the scribe. Thus, most of the corrosion that was observed initiated at the edges of the samples. In outdoor exposure, the edges and bottom of the panels stayed wetter longer than the sun-exposed top surface. The usual “edge effects” (residual stress and thinning of the paint) coupled with ultraviolet embrittling of the coating contributed to the edge attack not typically seen in accelerated corrosion chamber tests.

The total impedance of a representative set of samples tested in outdoor exposure are given in figures 13–15. There was no real correlation between total impedance and corrosion performance of the pretreatment. Several samples had good corrosion performance and low impedance, while others had high impedance values with poor corrosion performance. That said, samples with high impedance and blistering may indicate that the pretreatment relies on barrier properties for protection and offers little resistance to undercutting. If the opposite is true, as in the case of chromate, the pretreatment may have inhibiting “self healing” qualities and provides better resistance to undercutting, but offers less barrier protection.

Figures 16 and 17 offer a comparison of the impedance values of the two controls in outdoor exposure with the laboratory impedance measurements of similarly prepared control samples in laboratory immersion. There appeared to be a similar trend with both sets of data, especially with the grit-blasted samples, which eventually leveled off at about 10^5 ohms. There was clearly more noise in the chromate data for both outdoor exposure and laboratory, perhaps as a product of the inhibiting qualities of chromate. Nevertheless, this comparison is offered as a verification of the degradation trends of the like-prepared control samples in outdoor exposure.

5. Conclusions

- The mode of failure in outdoor exposure was distinctly different from that typically seen in accelerated corrosion chambers. Corrosion attack at the edges was prevalent in outdoor exposure, while attack at scribe was uncommon.
- All samples maintained good adhesion (above 1500 psi), regardless of corrosion performance. A slight correlation between postexposure adhesion and corrosion performance was observed within samples of a given surface treatment.
- Postexposure adhesion was a function of surface treatment and not alloy dependant. Samples with a chemical pretreatment tended to maintain adhesion better than those without a chemical pretreatment (the exception being grit-blasted 2519 samples where postexposure adhesion was comparable to all others, including chromate).
- Alloy 2519 grit blasted with no pretreatment did surprisingly well, performing best of all the samples without a pretreatment, and nearly as well as chromate.
- Because of its superior ability to retard undercutting and inhibit corrosion, chromate was best at protecting the edges of samples as well as guarding against attack at the scribe. No other pretreatment was more consistent at protecting all three alloys than chromate.
- Regardless of the mode of failure observed in outdoor exposure, there was agreement with the performance results from accelerated corrosion tests and outdoor exposure. In both tests, Brent Chemcote performed best of the nonchromate pretreatments on all three alloys.

6. References

1. Dante, J. F.; Petry, L.; Peeler, D. T. Comparison of Laboratory Corrosion Test Methods and Outdoor Corrosion Test for Air Force Coating Systems. *1999 Tri-Service Corrosion Conference Proceedings*, Myrtle Beach, SC, November 1999.

2. Nowak, D. *Weldability Study of 2519-T87 Aluminum Armor*; U.S. Army Materials Technology Laboratory: Watertown, MA, May 1990.

3. Pickens, J. *Aluminum Armor 2519*: *A Review of Literature Relevant to the Advanced Amphibious Assault Vehicle*; technical report no. 99-95; Concurrent Technologies Corp.: Johnstown, PA, 13 January 2000.

4. National Center for Manufacturing Sciences. *Alternatives to Chromium for Metal Finishing*; final report NCMS no. 0273RE95; Ann Arbor, MI, October 1995.

5. Placzankis, B. E.; Beatty, J. H.; Kelley, J. V.; Krebs, L. *Evaluation of Nonchromate Conversion Coatings on Aluminum Armor Alloys;* paper no. 532; National Association of Corrosion Engineers (NACE) NACE International: Houston, TX, 1997.

6. MIL-C-53039A. *Coating, Aliphatic Polyurethane, Single Component, Chemical Agent Resistant* **1993**.

7. MIL-P-53022. *Primer, Epoxy Coating, Corrosion Inhibiting, Lead and Chromate Free* **1992**.

8. ATSM D 1654-79A. Standard Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments. *Annu. Book ASTM Stand.* **1984**.

9. ATSM D 4541. Standard Test Method for Pull-off Strength of Coated Specimens Subjected to Corrosive Environments. *Annu. Book ASTM Stand*. **1995**.

10. ASTM B117. Standard Method of Salt Spray (Fog) Testing. *Annu. Book ASTM Stand*. **1990**.

11. GM 9540P. Accelerated Corrosion Test. *General Motors Engineering Standards* **1997**.

Appendix A: Sample Designations, Pretreatments, and Alloy Combinations

Table A-1. Energy dispersive spectroscopy verification of aluminum alloy substrates.

Panel Identification	Set No.	Alloy Element	Alloy Designation	Pretreatment Type
A	a	Cu	2519	Grit blasted/no conversion coating
	b	Cu	2519	Grit blasted/no conversion coating
B	a	Mg	5083	Grit blasted/no conversion coating
	b	Mg	5083	Grit blasted/no conversion coating
C	a	MgZn	7039	Grit blasted/no conversion coating
	b	MgZn	7039	Grit blasted/no conversion coating
D	a	Cu	2519	Chromate - Alodine 1200
	b	Cu	2519	Chromate - Alodine 1200
E	a	Mg	5083	Chromate - Alodine 1200
	b	Mg	5083	Chromate - Alodine 1200
F	a	MgZn	7039	Chromate - Alodine 1200
	b	MgZn	7039	Chromate - Alodine 1200
G	a	MgZn	7039	Nonchromate - Brent Chemcoat L497260A
	b	MgZn	7039	Nonchromate - Brent Chemcoat L497260A
H	a	Mg	5083	Nonchromate - Brent Chemcoat L497260A
	b	Mg	5083	Nonchromate - Brent Chemcoat L497260A
I	a	Cu	2519	Nonchromate - Brent Chemcoat L497260A
	b	Cu	2519	Nonchromate - Brent Chemcoat L497260A
J	a	Mg	5083	Nonchromate - Turcoat Alcoat 6787
	b	Mg	5083	Nonchromate - Turcoat Alcoat 6787
K	a	MgZn	7039	Nonchromate - Turcoat Alcoat 6787
	b	MgZn	7039	Nonchromate - Turcoat Alcoat 6787
L	a	Cu	2519	Nonchromate - Turcoat Alcoat 6787
	b	Cu	2519	Nonchromate - Turcoat Alcoat 6787
M	a	Mg	5083	Nonchromate - Patclin 1910A
	b	Mg	5083	Nonchromate - Patclin 1910A
N	a	MgZn	7039	Nonchromate - Patclin 1910A
	b	Cu	2519	Nonchromate - Patclin 1910A
O	a	Cu	2519	Nonchromate - Patclin 1910A
	b	Cu	2519	Nonchromate - Patclin 1910A
P	a	MgZn	7039	Nonchromate - Patclin 1910B
	b	MgZn	7039	Nonchromate - Patclin 1910B
Q	a	Mg	5083	Nonchromate - Patclin 1910B
	b	Cu	2519	Nonchromate - Patclin 1910B
R	a	Cu	2519	Nonchromate - Patclin 1910B
	b	Cu	2519	Nonchromate - Patclin 1910B
S	a	Mg	5083	Nonchromate - Patclin 1910C
	b	Mg	5083	Nonchromate - Patclin 1910C
T	a	MgZn	7039	Nonchromate - Patclin 1910C
	b	MgZn	7039	Nonchromate - Patclin 1910C
U	a	Cu	2519	Nonchromate - Patclin 1910C
	b	Cu	2519	Nonchromate - Patclin 1910C
V	a	Cu	2519	Nonchromate - Bulk Chemical E-CLPS 923
	b	Cu	2519	Nonchromate - Bulk Chemical E-CLPS 923
W	a	MgZn	7039	Nonchromate - Bulk Chemical E-CLPS 923
	b	MgZn	7039	Nonchromate - Bulk Chemical E-CLPS 923
X	a	Mg	5083	Nonchromate - Bulk Chemical E-CLPS 923
	b	Mg	5083	Nonchromate - Bulk Chemical E-CLPS 923

Appendix B: Postexposure Pull-off Adhesion Results With Statistics

Table B-1. ASTM D 4541[12] coating adhesion lb/in^2 (psi).

Test Sample		Reading No.						Statistics	
Alloy	**Pretreatment**	**1**	**2**	**3**	**4**	**5**	**6**	**Average**	**Std. Dev.**
2519	Grit blast	1710	1750	2800	2400	—	—	2165	528
2519	Chromate	2500	2650	2400	1680	—	—	2308	431
2519	Chemcote	2320	2700	2790	2200	—	—	2503	287
2519	Turcoat	2010	2100	1350	2100	—	—	1890	362
2519	Patclin 1	1920	1810	2280	2450	2200	2050	2118	237
2519	Patclin 2	3200	2800	2560	2850	2700	2510	2770	249
2519	Patclin 3	2820	2600	2980	3200	—	—	2900	254
2519	Bulk Chemical	2200	2640	2500	2710	—	—	2513	226
5083	Grit blast	1800	1490	1800	2300	—	—	1693	478
5083	Chromate	2600	2950	2700	2710	—	—	2740	149
5083	Chemcote	2410	1700	2390	800	—	—	1825	759
5083	Turcoat	2150	2220	2350	2800	—	—	2380	292
5083	Patclin 1	1890	2000	2580	2450	—	—	2230	336
5083	Patclin 2	2190	1900	—	—	—	—	2045	205
5083	Patclin 3	1620	2200	2910	2530	—	—	2315	547
5083	Bulk Chemical	2590	2450	2500	2400	—	—	2485	81
7039	Grit blast	1780	1400	1480	1400	—	—	1515	181
7039	Chromate	2310	2400	2690	2090	—	—	2373	249
7039	Chemcote	2950	2000	2700	2275	—	—	2481	425
7039	Turcoat	2500	2025	2300	2400	—	—	2306	205
7039	Patclin 1	2690	2300	—	—	—	—	2495	276
7039	Patclin 2	2480	2600	2490	2450	—	—	2505	66
7039	Patclin 3	2310	2450	2890	2710	—	—	2590	260
7039	Bulk Chemical	2840	2900	2620	2600	—	—	2740	152

[1] ATSM D 4541. Standard Test Method for Pull-off Strength of Coated Specimens Subjected to Corrosive Environments. *Annu. Book ASTM Stand*. **1995**.

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Appendix C: Failure Mode Recording for Each Pull-off Test

Table C-1. Pull-off adhesion test failure modes.

Panel Identification	Set No.	First Reading	Second Reading
A	a	Substrate	Substrate
	b	Substrate	Adhesive/substrate
B	a	Substrate	Substrate
	b	Substrate/adhesive	Substrate/adhesive
C	a	Substrate	Substrate
	b	Substrate	Substrate
D	a	Adhesive/intralayer	Adhesive/substrate
	b	Adhesive	Adhesive
E	a	Adhesive/substrate	Intralayer
	b	Intralayer	Interlayer
F	a	Substrate/adhesive	Adhesive
	b	Adhesive/substrate	Substrate
G	a	Substrate	Substrate
	b	Adhesive/substrate	Adhesive/substrate
H	a	Intralayer/substrate	Intralayer/substrate
	b	Substrate	Substrate
I	a	Substrate	Intralayer
	b	Adhesive	Adhesive
J	a	Adhesive/substrate	Adhesive/substrate
	b	Substrate	Adhesive/substrate
K	a	Adhesive/substrate	Substrate/adhesive
	b	Substrate	Adhesive/substrate
L	a	Substrate	Substrate
	b	Substrate/adhesive	Substrate/adhesive
M	a	Adhesive/substrate	Adhesive/substrate
	b	Intralayer	Adhesive/substrate
N	a	Adhesive	Adhesive
	b	Substrate	Substrate
O	a	Substrate/adhesive	Adhesive/intralayer
	b	Substrate	Substrate
P	a	Intralayer	Intralayer
	b	Adhesive/substrate	Adhesive/substrate
Q	a	Substrate	Substrate
	b	Adhesive	Adhesive
R	a	Adhesive/substrate	Adhesive/substrate
	b	Adhesive	Intralayer
S	a	Substrate/adhesive	Substrate
	b	Adhesive/substrate	Adhesive
T	a	Adhesive	Adhesive
	b	Adhesive	Adhesive
U	a	Adhesive	Adhesive
	b	Adhesive	Adhesive/substrate
V	a	Adhesive	Adhesive/substrate
	b	Intralayer	Intralayer
W	a	Adhesive/intralayer	Adhesive/substrate
	b	Substrate	Adhesive/substrate
X	a	Adhesive	Substrate
	b	Intralayer	Adhesive

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